

**APPLICATION FOR UNITED STATES LETTERS PATENT**

for

**Method of Processing Seismic Data Acquired by  
Means of Multicomponent Sensors**

by

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Method of processing seismic data acquired by means of  
multicomponent sensors

GENERAL FIELD

5 The invention relates to techniques for processing  
seismic data acquired by means of multicomponent  
sensors.

This invention is in particular applicable to  
10 acquisition by means of cables disposed on the bottom  
of the sea (so-called "OBC" or "Ocean Bottom Cable"  
techniques).

Multicomponent geophones capable of working in any  
15 position whatsoever, in particular at the bottom of the  
sea, have recently been proposed. This "omnitilt" probe  
technology has allowed new simplified cables  
(mechanical joints are no longer necessary) and allows  
acquisitions with a better seismic bandwidth.

20 However, the acquisition step does not make it possible  
to provide the true orientation of the geophones of the  
cable, although this information is indispensable for  
making it possible to process the data.

25 The invention proposes a processing which is intended  
to be implemented on raw data and which allows  
reorientation and calibration (intended to convert the  
measurements of various geophones into a common phase  
30 and amplitude response).

STATE OF THE ART

Techniques consisting in isolating from the signal the  
35 data which correspond to the first arrival at the  
sensor and in determining on the basis of these data a  
filter intended to be applied to the raw data so as to  
correct them and to thus obtain the components of the  
signal on the expected axes have already been proposed.

A proposal to this effect has been described in the article:

5 "Horizontal vector infidelity correction by general linear transformation" - Joe Dellinger et al. - SEG - 9-14 September 2001.

10 However, this technique is not necessarily optimal since the coupling mechanism which intervenes at the geophone level is not the same for the waves which correspond to a first arrival at the sensor and for the waves reflected or converted by the seismic horizons.

#### PRESENTATION OF THE INVENTION

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The invention proposes another approach which employs the true data window for numerically reconstructing geophones oriented along the desired axes.

20 Implicitly, this approach compensates for the errors which are not related to the geophones themselves, but which are due to the fact that the coupling between the geophone and the waves to be recorded is different depending on whether it is necessary to make a vertical  
25 vibration movement rather than a horizontal movement (on account of gravity).

30 In the case of a cable, the coupling is furthermore different depending on whether the vibration movement is in the direction of the cable or transverse.

Moreover, since deeper windows are subject to a lower S/N (signal-to-noise) ratio, processing which implements trace stacks is moreover used.

35

The invention thus proposes, according to a first aspect, a method of processing seismic data acquired by means of a sensor having at least three geophone components, characterized in that estimators are

determined which are combinations of these components making it possible to isolate the various data depending on whether they correspond to propagation with reflection or with conversion and in that, to  
5 determine a sensor reconstruction, the operators to be applied to the various components of the sensor are determined in such a way as to minimize the deviation between reference data and data obtained by applying the estimators to the sensor reconstruction, the  
10 operators thus determined being applied to the data acquired.

It is specified here that, in the remainder of the present text, the term geophone is understood to mean  
15 any velocity sensor and the term hydrophone any pressure sensor.

Preferred, but non limiting aspects of the method according to the first aspect of the invention are the  
20 following:

- the sensor furthermore including a hydrophone, the reference data for reconstructing a vertical geophone are derived from the data acquired by the hydrophone;
- the reference data for reconstructing a vertical  
25 geophone without hydrophone or for reconstructing horizontal geophones are derived from the application of the estimators to one of the geophones of the sensor;
- the orientation in the horizontal plane of a  
30 geophone component is obtained by minimizing the estimator of the transverse reflection;
- the estimators are determined as a function of a model of isotropic propagation or including the azimuthal anisotropy.

35 According to another more general aspect, the invention proposes a method of processing seismic data acquired by means of a sensor having at least three geophone components, characterized in that estimators are

determined which are combinations of these components making it possible to isolate the various data depending on whether they correspond to propagation with reflection or with conversion. The estimators thus  
5 determined may find applications other than that forming the subject of the method according to the first aspect of the invention.

#### DESCRIPTION OF THE FIGURES

10

- Figure 1 is a diagrammatic representation giving the angular conventions used;

- Figures 2 and 3 are flow charts giving the various steps of the processing respectively in one and the  
15 other of the two exemplary implementations described.

#### DESCRIPTION OF ONE OR MORE MODES OF IMPLEMENTATION OF THE INVENTION

##### 20 First exemplary implementation: case of an isotropic propagation model

Under the assumption of a locally 1D (one dimensional) geology in proximity to the receivers, and assuming  
25 isotropic propagation of the earth, a given geophone, with an orientation  $\phi \psi$ , measures:

$$m_k = R_{pp} \cos(\psi) \delta_{ppk} + (R_{ps} \cos(\theta_k - \phi) + R_{trsv} \sin(\theta_k - \phi)) \sin(\psi) \delta_{psk}$$

30

With :

k : index for the shotpoint (from 1 to N)

$\theta_k$  : azimuth of the shotpoint with respect to the abscissa axis

35

$R_{pp}$  : reflectivity PP

$\delta_{pp}$  : dynamic correction PP ("normal moveout" or NMO)

$R_{ps}$  : isotropic radial reflectivity PS

Rtrsv : isotropic transverse  
reflectivity PS  
 $\delta_{ps}$  : dynamic correction PS ("normal  
moveout" or NMO)

5

This model allows the evaluation of the reflectivity parameters from the set of traces  $tr_k$  through simple processing of least squares comparison (ignoring  $\psi$  to begin with) in the Fourier domain, leading to the following equations:

10

$$\begin{pmatrix} \frac{N}{wc(\varphi)} & wc(\varphi) & ws(\varphi) \\ \frac{wc(\varphi)}{ws(\varphi)} & Sc2(\varphi) & Scs(\varphi) \\ ws(\varphi) & Scs(\varphi) & Ss2(\varphi) \end{pmatrix} \cdot \begin{pmatrix} Rpp \\ Rps \\ Rtrsv \end{pmatrix} = \begin{pmatrix} Sv_x \\ Shcx(\varphi) \\ Shsx(\varphi) \end{pmatrix}$$

Scalar quantities:

15

$$\begin{aligned} Sc(\phi) &= \sum_k \cos(\theta_k - \phi) & Ss(\phi) &= \sum_k \sin(\theta_k - \phi) \\ Sc2(\phi) &= \sum_k \cos^2(\theta_k - \phi) & Ss2(\phi) &= \sum_k \sin^2(\theta_k - \phi) \\ Scs(\phi) &= \sum_k \cos(\theta_k - \phi) \sin(\theta_k - \phi) \\ N &= Sc2 + Ss2 \end{aligned}$$

20

Wavelet quantities:

$$wc(\phi) = \sum_k \cos(\theta_k - \phi) \delta_{ps_k} \delta_{pp_k}^{-1}$$

$$25 \quad ws(\phi) = \sum_k \sin(\theta_k - \phi) \delta_{ps_k} \delta_{pp_k}^{-1}$$

Trace stack quantities for geophone x:

$$Sv_x = \sum_k x_k \delta_{pp_k}^{-1}$$

$$30 \quad Shcx(\phi) = \sum_k \cos(\theta_k - \phi) x_k \delta_{ps_k}^{-1}$$

$$Shsx(\phi) = \sum_k \sin(\theta_k - \phi) x_k \delta_{ps_k}^{-1}$$

The solution of this linear system gives:

$$35 \quad \Delta_{iso} Rpp \cos(\psi) = W Sv_x + (Scs ws - Ss2 wc) Shcx + (Scs wc - Sc2 ws) Shsx$$

$$\Delta_{iso} Rps \sin(\psi) = Kis \cos(\phi) - Kic \sin(\phi)$$

$$\Delta_{iso} R_{trsv} \sin(\psi) = K_{is} \cos(\phi) - K_{ic} \sin(\phi)$$

With:

$$W = Sc2 \ Ss2 - Scs^2$$

$$5 \quad \Delta_{iso} = WN + wc(Scs \overline{ws} - Ss2 \overline{wc}) + ws(Scs \overline{wc} - Sc2 \overline{ws})$$

$$K_{ic} = (Scs \overline{ws} - Ss2 \overline{wc}) S_{vx} + (N Ss2 - ws \overline{ws}) Sh_{cx} + (-N Scs + ws \overline{wc}) Sh_{sx}$$

$$K_{is} = (Scs \overline{wc} - Sc2 \overline{ws}) S_{vx} + (-N Scs + wc \overline{ws}) Sh_{cx} + (N Sc2 - wc \overline{wc}) Sh_{sx}$$

This modelling allows evaluations taking account of the following properties:

- 10 a.  $R_{pp}$  does not depend on  $\phi$ ,
- b.  $|R_{ps}|^2 + |R_{trsv}|^2$  does not of course depend on  $\phi$  either,
- c.  $\Delta_{iso}$  is in practice rapidly steady over time and can be ignored for the calibration/orientation
- 15 procedure, since it is common to all the geophones of one and the same receiver.

#### Evaluations of dense shots

- 20 Most of the OBC acquisitions are gleaned using a dense and regular grid of sources, which allows considerable simplification:

$Sc = Ss = 0, wc = ws = 0$  (symmetry of the sources with respect to the receivers)

- 25  $Scs = 0 \ Sc2 = Ss2 = N/2$  (isotropic source distribution)

Next, the exact solution can be obtained through the approximation:

$$N R_{pp} \cos(\psi) = S_{vx}$$

$$30 \quad N R_{ps} \sin(\psi) = 2 Sh_{cx}(\phi)$$

$$N R_{trsv} \sin(\psi) = 2 Sh_{sx}(\phi)$$

- This approximation leads to very simple calculations, not involving any wavelets, and can be applied
- 35 immediately.

#### Orientation of the geophones

Since Rtrsv does not exist physically, the minimization of the energy of Rtrsv leads to a trigonometric equation which gives the true orientation  $\phi_{geo}(+k \pi)$ :

$$5 \quad \tan(2 \phi_{geo}) = 2 \frac{(\sum_i K_{ic}, K_{is})}{(\sum_i K_{ic}^2 - \sum_i K_{is}^2)}$$

$((E_{max}-E_{min})/(E_{max}+E_{min}))^{1/2}$  gives a check on the quality of the reorientation.

10 Moreover, if one wishes to find the orientation according to the first arrivals, it is possible to correct the said first arrivals so as to set them to one and the same arrival time, then to simplify kic and kis by replacing the wavelets wc and ws by the scalars  
15 sc and ss, by considering that the waves recorded horizontally are in fact the projection of the radial wave P, present on all the geophones since it is oblique.

#### 20 Geophone vertical composite calibration:

With the geophones  $g_1, g_2, g_3$ , we construct a vertical composite geophone v,  $v = op_1 * g_1 + op_2 * g_2 + op_3 * g_3$  (or  
25 comprising additional similar terms in the case where extra geophones are present in the receiver) where  $op_1, op_2, op_3$  are the filters of finite length and  $op_u * g_u$  represents the convolution of geophone  $g_u$  with filter  $op_u$ .

30 such that:

$$E1 = |XH - XV|^2 = |K_{ic}(v)|^2 + |K_{is}(v)|^2$$

The energy of the difference between XH (hydrophone  
35 after application of the geophone phantom, or cross-ghost hydrophone) and XV (the vertical composite geophone after application of the hydrophone phantom or



cross-ghost geophone), (see for example in this regard the Applicant's Patent Application FR 2 743 896).

$$E2 = |Rps(v)|^2 + |Rtrsv(v)|^2$$

5 horizontal energy of the vertical composite,

$E = \lambda E1 + (1-\lambda)E2$  is a quadratic form in the coefficients of the filters and can be reduced to the minimum, thus giving a linear system to be solved. ( $\lambda$  is a matching parameter,  $0 \leq \lambda \leq 1$ , which favours either a greater adjustment to the reference hydrophone or a greater minimization of the shear energy).

15 In the case of terrestrial data, that is to say if there is no hydrophone available, it is possible to choose one of the geophones as reference and to replace the hydrophone by  $Rpp(g_{ref})$ .

#### Calibration in a horizontal arbitrary direction

20

With  $g = op_1 * g_1 + op_2 * g_2 + op_3 * g_3$  and  $\varphi_g$  an arbitrary direction,

We define:

$$E1 = |Rps(g, \varphi_g) - Rps(ref, \varphi_{ref})|^2,$$

25 as being the energy of the difference between the evaluation of Rps of the arbitrary composite geophone and the evaluation of Rps of a reference geophone (in general the geophone oriented in the direction of the cable).

30

$$E2 = |Rpp(g)|^2 + |Rtrsv(g, \varphi_g)|^2 \text{ (the nonradial energy)}$$

$E = \lambda E1 + (1 - \lambda)E2$  allows the derivation of a composite horizontal geophone in the desired direction, having the same frequency response as the reference geophone, and with a minimum PP contamination.

35

Considering the cases  $\varphi_{\text{ref}} = 0$  and  $\varphi_{\text{ref}} = \pi/2$ , it is possible by simple trigonometric combination to generate the radial and transverse projections.

## 5 Second exemplary implementation: case of anisotropic azimuthal propagation modelling

Let  $\alpha$  be the direction of the natural fast propagation axis. The modelling of the measurement of the geophone becomes (using one or other of  $R_{ps1}$  and  $R_{ps2}$  the two images along the natural directions, or  $R_{ps}$  and  $\delta R_{ps}$  defined by  $R_{ps1} = R_{ps} + \delta R_{ps}$ ,  $R_{ps2} = R_{ps} - \delta R_{ps}$ ):

$$\begin{aligned} m_k &= R_{pp} \cos(\psi) \delta p p_k + (R_{ps1} \cos(\varphi - \alpha) \cos(\theta_k - \alpha) + R_{ps2} \sin(\varphi - \alpha) \sin(\theta_k - \alpha)) \sin(\psi) \delta p s_k \\ m_k &= R_{pp} \cos(\psi) \delta p p_k + (R_{ps} \cos(\theta_k - \varphi) + \delta R_{ps} \cos(\theta_k + \varphi - 2\alpha)) \sin(\psi) \delta p s_k \end{aligned}$$

giving the normal equations

20

$$M = \begin{pmatrix} N & wc(\varphi) & wc(2\alpha - \varphi) \\ \overline{wc(\varphi)} & Sc2(\varphi) & Sc2(\alpha) - N \sin^2(\alpha - \varphi) \\ \overline{ws(2\alpha - \varphi)} & Sc2(\alpha) - N \sin^2(\alpha - \varphi) & Sc2(2\alpha - \varphi) \end{pmatrix}$$

$$M \cdot \begin{pmatrix} R_{pp} \\ R_{ps} \\ \delta R_{ps} \end{pmatrix} = \begin{pmatrix} S_{vx} \\ Shcx(\varphi) \\ Shcx(2\alpha - \varphi) \end{pmatrix}$$

The solution of this linear system gives:

$$\begin{aligned} \Delta_{\text{iso}} R_{pp} \cos(\psi) &= \text{unchanged} \\ \Delta_{\text{aniso}} R_{ps} \sin(\psi) &= (K_{ac} \cos(2\alpha - \varphi) + K_{as} \sin(2\alpha - \varphi)) \sin(2(\alpha - \varphi)) \\ \Delta_{\text{aniso}} R_{trsv} \sin(\psi) &= (-K_{ac} \cos(\varphi) - K_{as} \sin(\varphi)) \sin(2(\alpha - \varphi)) \end{aligned}$$

30 With:

$$\Delta_{\text{aniso}} = \sin^2(2(\alpha - \phi)) \Delta_{\text{iso}}$$

$$K_{ac} = (Sc^2 \overline{ws} - Scs \overline{wc}) Svx + (N Scs - wc \overline{ws}) Shcx - (N Sc^2 - wc \overline{wc}) Shsx$$

$$5 \quad K_{as} = (-Ss^2 \overline{wc} + Scs \overline{ws}) Svx + (N Ss^2 - ws \overline{ws}) Shcx - (N Scs - ws \overline{wc}) Shsx$$

Vertical calibration of composite geophone:

- 10 The isotropic process remains applicable with the change

$$E^2 = |K_{ac}(g)|^2 + |K_{as}(g)|^2$$

Horizontal arbitrary calibration or rows/columns of composite geophones

15

The observation of  $\delta Rps$  over the data field makes it possible to diagnose the presence (or otherwise) of significant azimuthal anisotropy. (the quantity  $\sin^2(2(\alpha - \phi)) \delta Rps$  does not require a knowledge of  $\alpha$  for its calculation).

20

The isotropic process remains applicable with the changes

25

$$E^2 = |\delta Rps(v)|^2 \text{ and } E = \lambda(E_1 + E_2) + (1 - \lambda)E_3.$$

When  $\alpha$  is not generally known, a scan over a range of  $\pi/2$  is implemented, using the value of  $\alpha$  which minimizes  $E_{\text{mini}}/E_0$ .

CLAIMS

1. Method of processing seismic data acquired by  
5 means of a sensor having at least three geophone  
components, characterized in that estimators are  
determined which are combinations of these components  
making it possible to isolate the various data  
10 depending on whether they correspond to propagation  
with reflection or with conversion and in that, to  
determine a sensor reconstruction, the operators to be  
applied to the various components of the sensor are  
determined in such a way as to minimize the deviation  
15 between reference data and data obtained by applying  
the estimators to the sensor reconstruction, the  
operators thus determined being applied to the data  
acquired.
2. Method according to Claim 1, in which, the sensor  
20 furthermore including a hydrophone, the reference data  
for reconstructing a vertical geophone are derived from  
the data acquired by the hydrophone.
3. Method according to Claim 1, in which the  
25 reference data for reconstructing a vertical geophone  
without hydrophone or for reconstructing horizontal  
geophones are derived from the application of the  
estimators to one of the geophones of the sensor.
- 30 4. Method according to Claim 1, characterized in that  
the orientation in the horizontal plane of a geophone  
component is obtained by minimizing the estimator of  
the transverse reflection.
- 35 5. Method according to one of the preceding claims,  
characterized in that the estimators are determined as  
a function of a model of isotropic propagation or  
including the azimuthal anisotropy.

6. Method of processing seismic data acquired by means of a sensor having at least three geophone components, characterized in that estimators are  
5 determined which are combinations of these components making it possible to isolate the various data depending on whether they correspond to propagation with reflection or with conversion.

**ABSTRACT**

5           The invention relates to a method of processing seismic data acquired by means of a  
sensor having at least three geophone components, characterized in that estimators are  
determined which are combinations of these components making it possible to isolate the  
various data depending on whether they correspond to propagation with reflection or with  
conversion. The estimators find application in particular for determining a sensor  
10 reconstruction according to which the operators to be applied to the various components of  
the sensor are determined in such a way as to minimize the deviation between reference data  
and data obtained by applying the estimators to the sensor reconstruction, the operators thus  
determined being applied to the data acquired.

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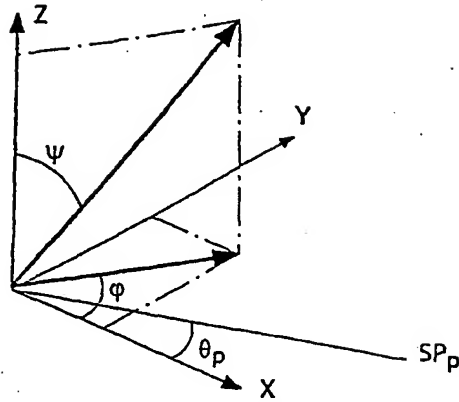


FIG.1

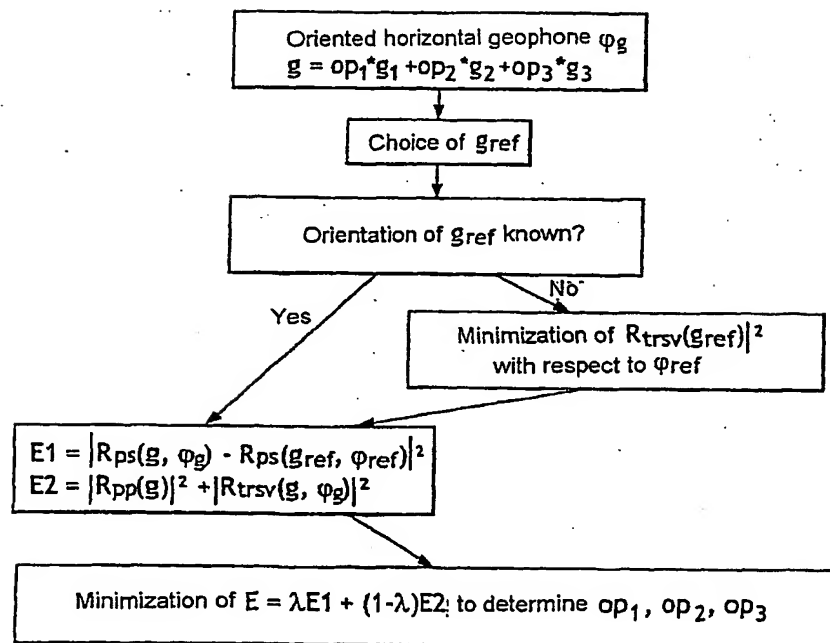


FIG.2

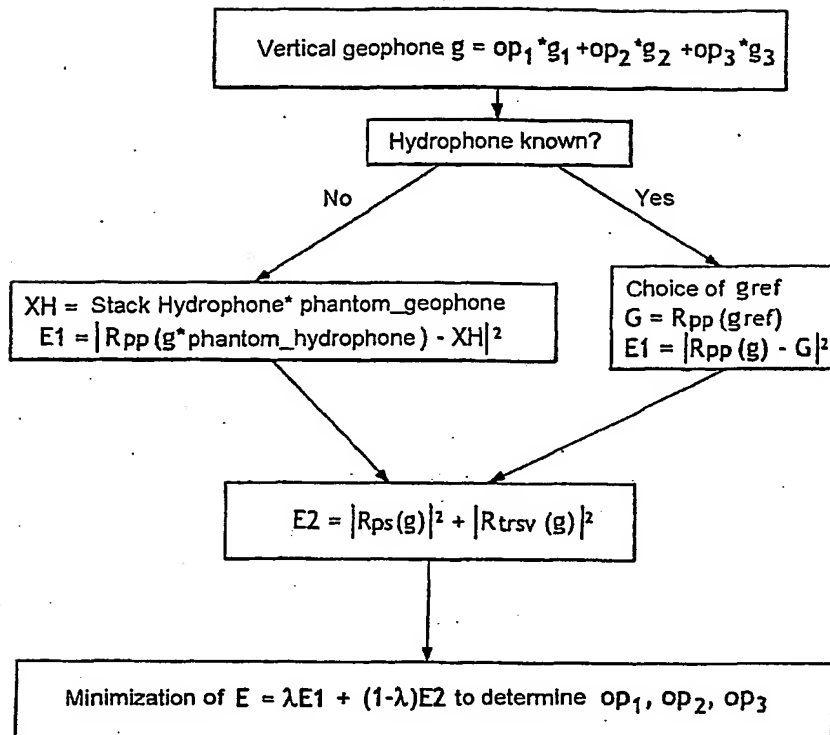


FIG.3